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Supplementary Notes on Sea-Surface Temperature Anomalies and Model-Generated Meteorological Histories[1]

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ABSTRACT—In seasonal computations, the Mintz-Arakawa two-level model is found to be sensitive to a minor alteration in the computational program. Effects of the program change on monthly mean sea level pressure fields are small in the first month but large in the second and third months, although the meteorological histories generated by both the original and modified programs are equally credible.

The inherited effects of a transient (1-mo) sea-surface temperature (SST) anomaly on the computed monthly mean sea level pressure fields over a period of a season are about as large in absolute magnitude as those generated in the model by a persistent (seasonal) SST anomaly.

The effects of a transient SST anomaly in the North Pacific Ocean on monthly and seasonal temperature and precipitation in the eastern United States may be large enough to produce a change of one or two class intervals in these predicted weather elements. The model-generated precipitation in the equatorial region is also found to be sensitive to the sea-surface temperature field in the North Pacific.

1. INTRODUCTION

In earlier reports (Spar 1972, 1973*a*, 1973*b*), we have described some results of numerical experiments with the two-level Mintz-Arakawa global general circulation model (Gates et al. 1971) in which a certain persistent positive anomaly pattern was superimposed on the sea-surface temperature (SST) field for a period of 3 mo. This note describes some further calculations that were carried out as part of the same experimental program but have not been previously reported. Like the experiments already described, these new computations were also designed to estimate the influence of SST anomalies on the behavior of the atmosphere over periods of time from 1 mo to a season, and to provide some background for studies in long-range weather prediction. Although the new experiments were not entirely successful (for reasons which are discussed later), the results may nevertheless be of some interest.

One basic question that arises regarding the response of the atmosphere to an SST anomaly concerns the duration or persistence, of the anomaly field. In the previously reported experiments, an SST anomaly pattern in the extra-tropical Pacific Ocean was held fixed for 3 mo. The 3-mo model history corresponding to this so-called "anomaly run" was then compared with a 3-mo "control run," identical in every respect except for the absence of the SST anomaly pattern. In the new computations, the Northern Hemisphere winter experiment (one of the three original experiments conducted) was repeated with the same initial state, and with the same positive SST anomaly (maximum, 6°C) located in the same region of the North Pacific Ocean (centered on latitude 32°N, longitude 160°W). This time, however, the warm oceanic pool was allowed to persist for only 1 mo of the anomaly run, after which time the control SST field, represented by the climatological mean annual SST pattern, was restored. How would the atmosphere respond to only 1 mo of anomalous thermal forcing compared with a season of the same SST anomaly? It was our intention to compare the two sets of meteorological histories to answer this question. Unfortunately, this proved impossible because of an unanticipated minor change in the computational program at GISS[3] between the two experiments. The program change[4], which was intended only as an optimization device, resulted in the separation of what should have been two identical model histories after about 2 weeks, a result very similar to that exhibited in various predictability experiments. Thus, the two sets of SST anomaly experiments were not comparable, and the question above could not be answered directly. Although the program modification eliminated the possibility of comparing a transient 1-mo anomaly with a persistent seasonal anomaly, it inadvertently provided an opportunity to examine the effect of a computational perturbation on extended time integrations with the model. In the first part of this note, the solutions generated by the modified program, hereafter referred to as the "fast" program, are compared with the corresponding solutions computed with the original program. Furthermore, in the course of the 1-mo anomaly experiment with the fast program, certain

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[4] The program change introduced was only a faster algorithm for computing the function p^κ, where p is pressure and $\kappa(=R/c_p)$ is the Poisson constant. The two algorithms give identical results up to four to six digits over the range of p from 50 to 1050 mb.

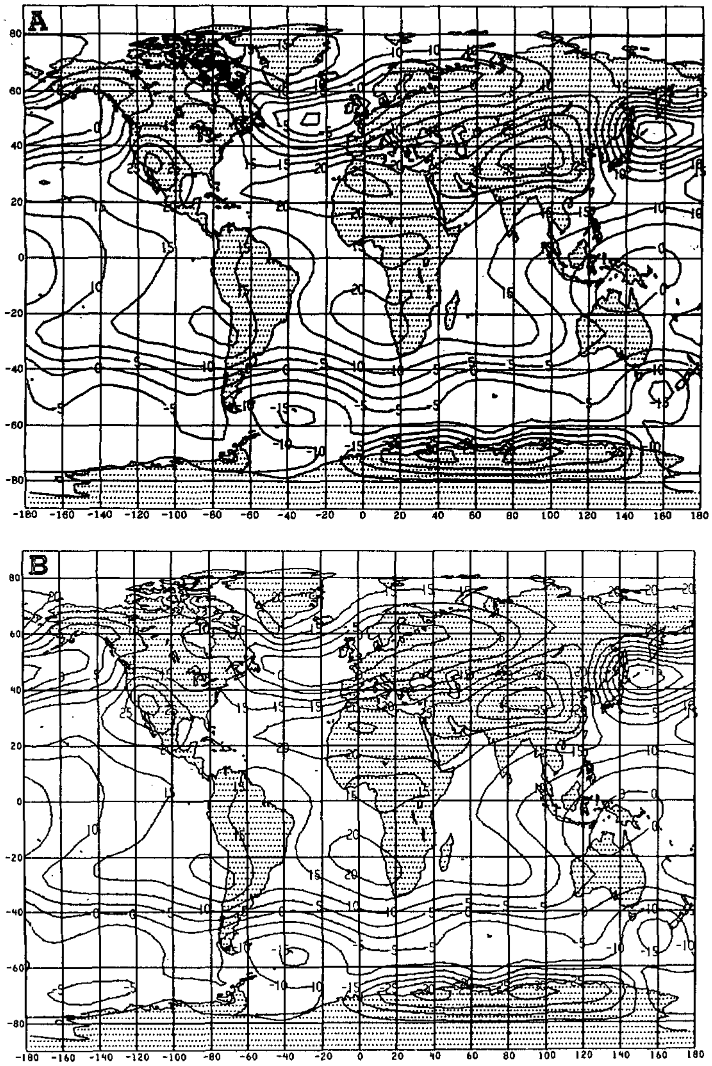

FIGURE 1.—Monthly mean sea level pressure field for days 1–30 of the Northern Hemisphere winter control run for (A) the original program and (B) the fast program. The isobar interval is 5 mb.

new calculations were performed. These are presented in the latter part of this paper.

2. EFFECTS OF THE PROGRAM CHANGE

A comparison of the control histories generated by the original and fast programs should reveal the effects of the program change over the total 3-mo period. A similar comparison of the corresponding original and fast anomaly runs is valid only for the first month, after which time the differences are due to both the program change and the differences between the SST fields. Hence, for the first 30 days, we may use either the control or anomaly histories to determine the effect of the program change. However, beyond 30 days, only the control runs can be employed for this purpose.

In both the anomaly and control runs, there is virtually no detectable difference between the daily global sea-level pressure fields generated by the original and fast programs for the first 12 days. Up to day 9, the maximum difference at any gridpoint is less than 2 mb. On day 12, the maximum difference exceeds 5 mb; in general, however, the differences are much smaller, and the pressure patterns are almost identical. However, on day 14, significant differences between the synoptic patterns begin to appear, with absolute differences of sea-level pressure in excess of 8 mb. These differences continue to increase, especially in the Northern Hemisphere; by the end of the month, the differences between any two corresponding daily control (or daily anomaly) maps, computed respectively with the original and fast programs, are at least as large as the differences between an anomaly map and its corresponding control map. The cumulative effect of the computational differences between the original and fast programs on the daily sea-level pressure fields is similar to that found in predictability experiments starting from two initial states that differ from each other by only some small random error distribution (e.g., National Academy of Sciences 1966). After about 2–3 weeks, the two solutions diverge, becoming effectively as uncorrelated as any two randomly selected fields.

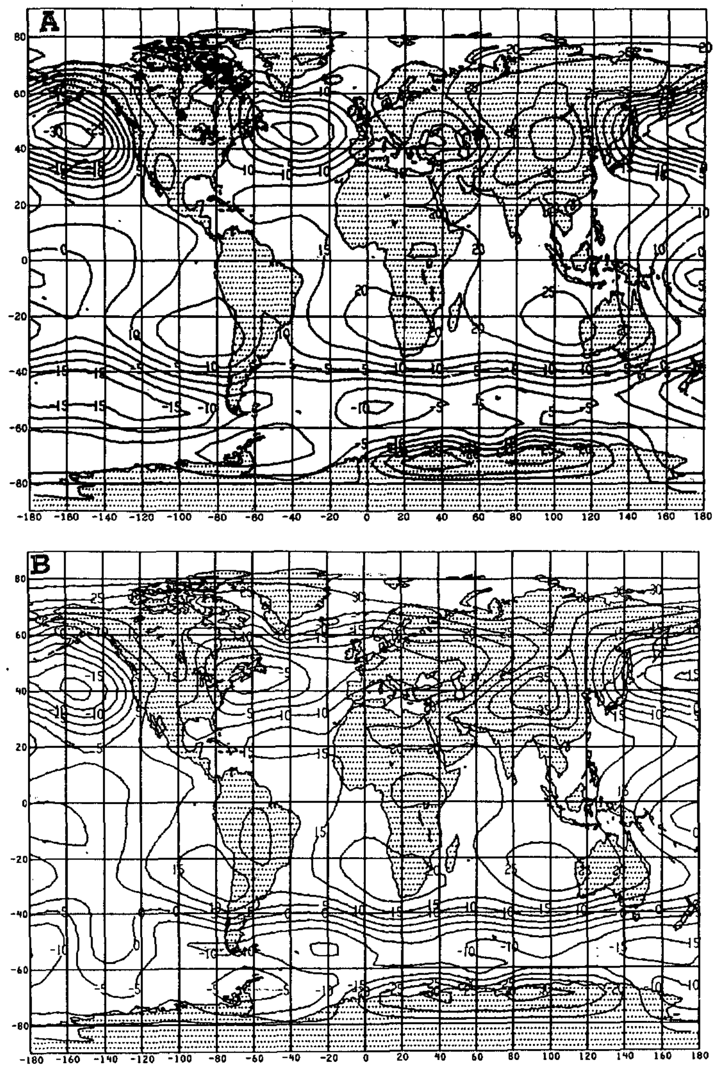

FIGURE 2.—Same as figure 1 for days 31–60.

Despite the limit on predictability of daily patterns indicated above, time averaging may be expected to reduce the differences between the solutions computed by the two programs. This is illustrated in figure 1, which shows the 30 day mean sea level pressure fields for the first 30 days of the control history as generated by the original and fast programs, respectively. Although some quantitative differences between the monthly mean pressures can be seen, notably in the North Atlantic Ocean, the two patterns are virtually identical for the first month. After the first month, however, even 30-day averaging fails to smooth out the differences between the two control histories. As shown in figure 2, the mean sea level pressure maps for the second month (days 31–60) of the control history, as computed with the original and fast program, respectively, are quite different both in quantitative detail and in major pattern features. Except for the subtropical high-pressure cells in the Southern Hemisphere, every major pressure system has been altered by the program change. Thus, the depth of the North Pacific cyclone is changed, the depth of the North Atlantic cyclone is changed, and the position of the center is shifted as well the Asiatic anticyclone is shifted, and the pressure pattern in the South Pacific is completely altered.

In the third month, represented in figure 3 by the mean of days 61–90, pressure difference between the original and fast programs are apparent in the subtropical latitudes of the Southern Hemisphere as well as in the Tropics. However, the most striking effect of the program change is seen in the North Atlantic where the fast program has generated a deep cyclone that is not in evidence in the original solution. This sensitivity of the model to a relatively minor program alteration is indicative of the difficulty of forecasting even the time-averaged monthly and seasonal pressure patterns with a dynamical model. Although both sets of solutions for the second and third months appear realistic and are equally credible, they obviously connot both represent correct predictions. The combined effect of uncertainty in the initial state together with the "computational uncertainty" noted here places a severe limit at the present time on both the application of dynamical models to monthly and seasonal forecasting and the credibility of the results of anomaly experiments.

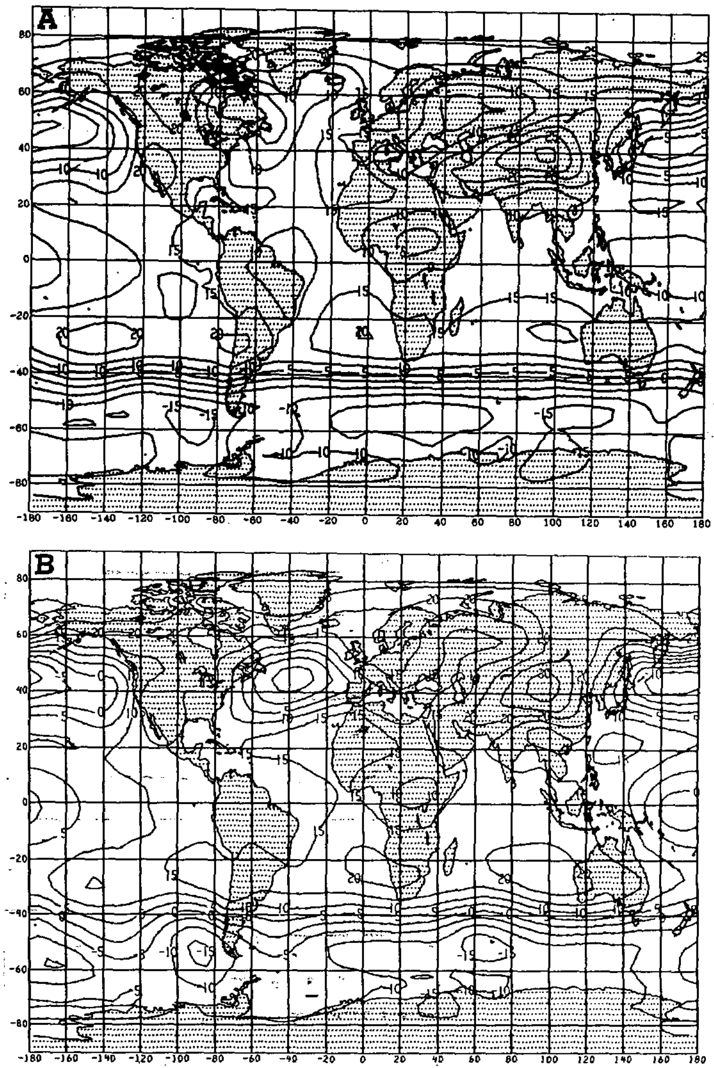

FIGURE 3.—Same as figure 1 for days 61–90.

3. QUALITATIVE COMPARISON OF THE RESPONSES TO TRANSIENT AND PERSISTENT SST ANOMALIES

Although the program change referred to previously made it impossible to compare in quantitative detail the results of the two experiments (i.e., the transient 1-mo anomaly versus the persistent seasonal anomaly), it is nevertheless possible to extract some qualitative information from the computations. For example, one can determine whether the anomaly minus control pressure differences 2 mo after the SST anomaly was removed indicate a larger or smaller carry-over effect than that resulting from the persistent warm pool.

The transient and persistent SST anomaly experiments are compared in figures 4, 5, and 6 for the first, second, and third months, respectively. Each figure shows the difference between the 30-day mean sea level pressure fields for the anomaly run and the corresponding control run. Figures 4A, 5A, and 6A represent the case of the persistent SST anomaly for each 30-day period and were computed with the original program; figures 4B, 5B, and 6B represent the case of the transient (first month only) SST anomaly for each period and were computed with the fast program.

In figure 4, representing the first month, the two anomaly minus control pressure difference fields should be identical, if the computational program had not been altered. The two difference fields are indeed similar, with differences close to zero over most of the earth in both experiments. One major effect of the North Pacific SST anomaly, which appears in both figure 4A and 4B, is a negative difference in excess of 10 mb on the West Coast of North America. On the other hand, an equally large negative presseur effect over Labrador in the original computation (fig. 4A) is not found in the fast computation (fig. 4B) although qualitatively the patterns are similar on the two maps.

The anomaly minus control pressure differences in the second month (fig. 5) are, as might be expected, quite different for the two experiments. In view of the effect of the program change noted previously, a detailed comparison of the two fields would be of little value. It is worth noting, however, that the *magnitude* of the residual pressure effect

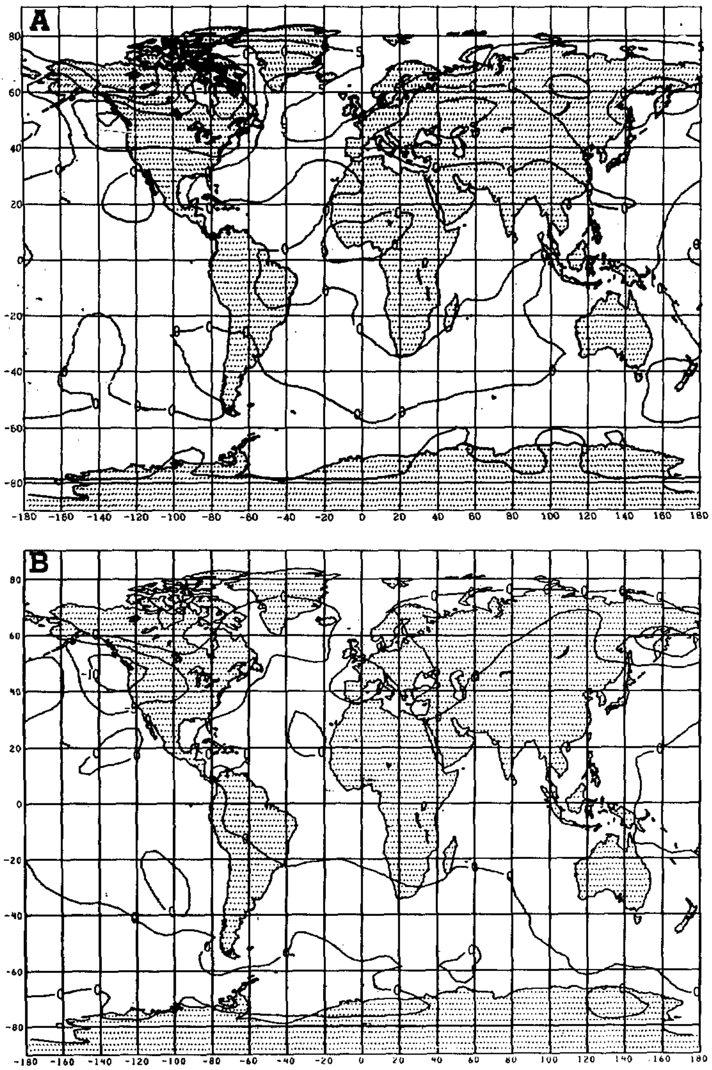

FIGURE 4.—Anomaly minus control sea level pressure differences for first month (days 1–30) of northern winter experiment for (A) the persistent SST anomaly and original program and (B) the transient SST anomaly and fast program.

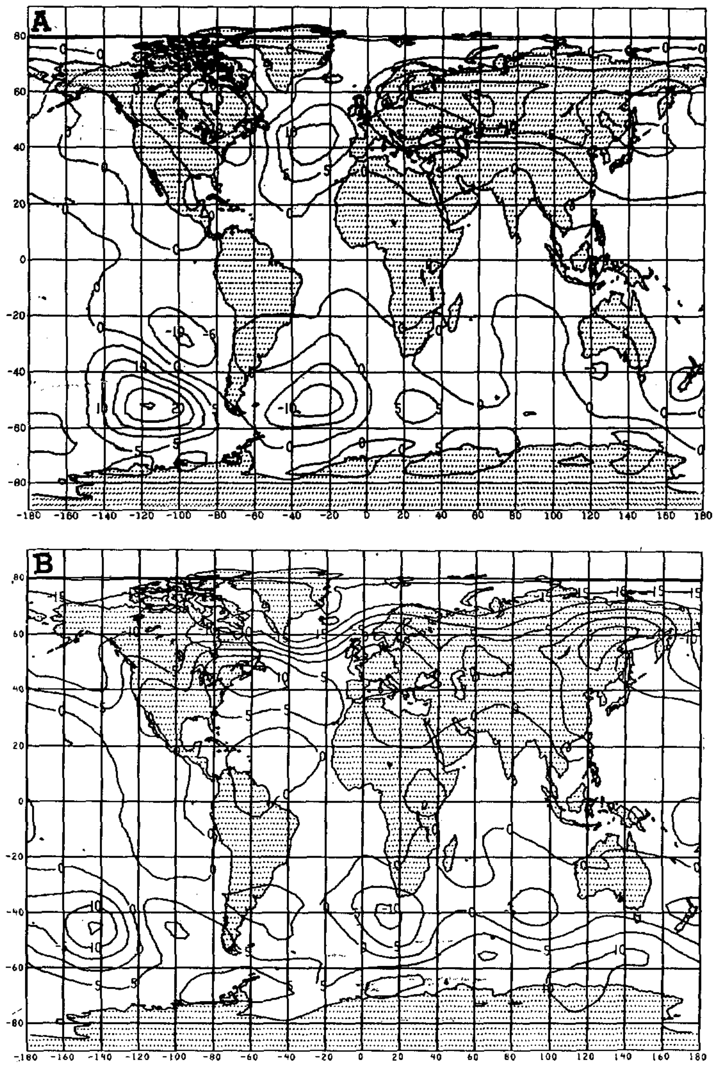

FIGURE 5.—Same as figure 4 for the second month (days 31–60).

left after removal of the transient warm pool, as represented by figure 5B, is no smaller in the Northern Hemisphere than that associated with the persistent warm pool, as shown in figure 5A. In the Southern Hemisphere, on the other hand, the magnitude of the response is weaker in the former case than in the latter. The range of mean sea level pressure differences over the globe in the second month is from −25 to +12 mb for the transient SST anomaly compared with −20 to +25 mb for the persistent anomaly.

From a visual comparison of the two maps in figure 6, it is apparent that the major effects of the persistent anomalous thermal forcing, shown in figure 6A, are not reflected in the map (fig. 6B) representing the residual effect of the transient warm pool in the third month. The two major effects in the former case are the positive pressure difference in Greenland and the general meridional gradient of pressure differences in high latitudes of the Southern Hemisphere, neither of which appears in figure 6B. Thus, at first glance, the residual effect of the transient SST anomaly appears to diminish with time. However, the range of pressure differences over the globe in the third month is from −15 to +15 mb for the transient case compared with −15 to +20 mb for the persistent case. Thus, the magnitude of the effect is again almost as large in the transient case, although the pattern of effects appears to be better organized on a large scale in the case of the persistent warm pool.

Another indication of the effect of the transient SST anomaly, as compared with the persistent anomaly, is illustrated in figure 7, which shows the meridional profiles of the anomaly minus control differences between the zonally averaged 600-mb heights on day 90, the final day of each run for the two experiments. The solid curve represents the case of the persistent SST anomaly and was computed with the original program, while the dashed curve represents the case of the transient SST anomaly, which was computed with the fast program. Clearly, the magnitude of the effect is the same in both cases, although the distributions are different. In both the persistent and transient anomaly cases, there are large interdiurnal variations of the meridional difference profiles, so that the curves shown in figure 7 are in no sense "typical". (For example, the large effect in the equatorial region indicated by the dashed curve appeared only in the last

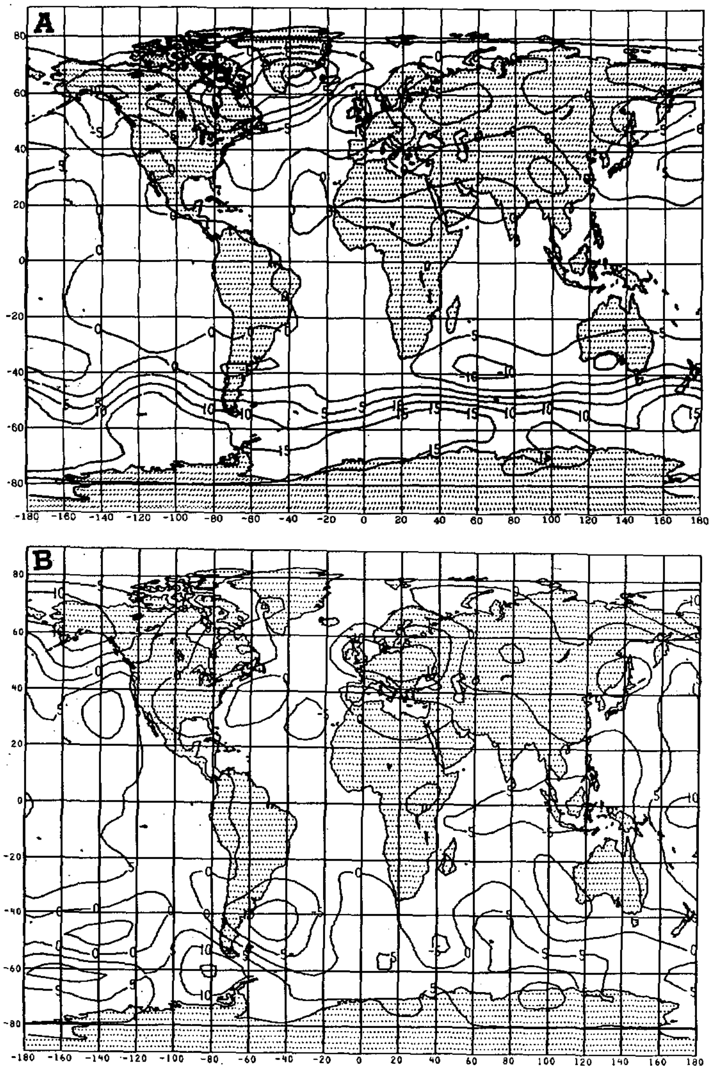

FIGURE 6.—*Same as figure 4 for the third month (days 61–90).*

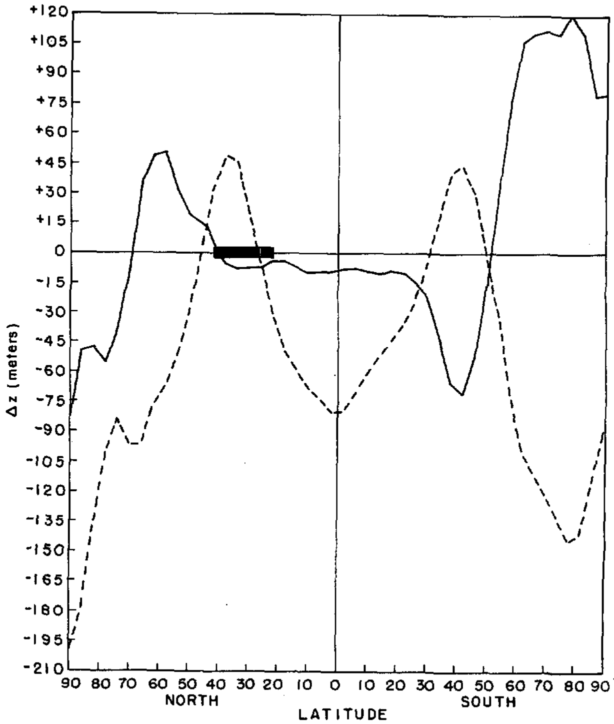

FIGURE 7.—Meridional profiles of anomaly minus control 600-mb height differences on day 90 for northern winter SST anomaly experiments. The solid curve represents the persistent anomaly and original program; the dashed curve represents the transient anomaly and fast program.

few days of the run with the transient anomaly.) However, the two curves are representative in the sense that they do indicate the relative magnitudes of the effects of transient and persistent SST anomalies.

The preceding results suggest that the magnitude of long-term (e.g., seasonal) effects of SST anomalies may be just as great for a transient (e.g., 1-mo) anomaly as for a persistent one, even though the form of the atmospheric response may be quite different. In the transient anomaly experiment, only the new initial conditions at the beginning of the second month are different for the anomaly run than for the control run. Any anomaly minus control pressure differences generated in this experiment after the first month are thus inherited effects of the anomalous thermal forcing that occurred in the first month. Although in time the atmosphere may "forget" its initial conditions and the inherited effect may decay, the rate of decay is apparently slow enough for such effects to be found at least 2 mo after the SST anomaly has been turned off. This apparent sensitivity of the model global atmosphere to local transient oceanic anomalies iudicates that the problem of extended and long-range prediction will probably not be solved until an interactive ocean-atmosphere model is successfully developed.

In view of the model's sensitivity to the computational perturbation just noted, as well as other evidence [5] of its extreme sensitivity to random perturbations in the initial state, one may question whether any conclusions at all can be drawn regarding the effects of persistent SST anomalies in the real atmosphere from the model experiments. Certainly, the noise level of the numerical experiments is now much too high for any signal generated by the SST anomalies to be clearly detected. At this point (and until some way can be found to reduce the noise level of the experiments), one can only argue that the solutions generated represent *possible* atmospheric responses and do give some indication of the possible magnitudes of the effects of the SST anomalies studied.

4. EFFECT OF A TRANSIENT SST ANOMALY ON TEMPERATURE AND PRECIPITATION

In the course of the experiment with the transient SST anomaly, a number of global and regional diagnostic quantities were calculated. Among these were the daily average surface temperature and average daily precipitation over the eastern region of North America, as well as daily and seasonal averages of zonal and global precipitation. A comparison of the anomaly and control results in terms of these "weather" parameters is presented in

[5] W. L. Gates of The Rand Corporation has recently reported (in a Symposium on Climatic Change held at the Scripps Institution of Oceanography in La Jolla, Calif. on Nov. 15–17, 1972) the results of numerical experiments, which clearly show that random perturbations of the initial state in the model lead to the generation of large amplitude "noise" in the 30-day mean pressure fields.

TABLE 1.—*Computed monthly and seasonal mean temperatures,* T *(°C), and total precipitation,* R *(cm), averaged over the eastern region for the anomaly, A, and control, C, runs. Differences (A−C) are also shown.*

	Month no. 1		2		3		Season	
Run	T (°C)	R (cm)	T	R	T	R	T	R
A	+6.1	7.15	+8.3	10.18	+5.0	7.03	+6.5	24.36
C	+4.6	8.34	+5.1	16.92	+6.7	11.36	+5.5	36.62
A−C	+1.5	−1.19	+3.2	−6.74	−1.7	−4.33	+1.0	−12.26

this section to indicate the possible climatic influence of the oceanic anomaly. (As we did not compute these same quantities for the persistent anomaly experiment, it is not possible to compare the relative magnitudes of the effects of the two types of SST anomalies.)

The eastern region is represented in the experiment by 30 gridpoints in the area bounded by latitudes 30° and 50°N and longitudes 70° and 90°W. A regional daily average is computed as the mean of 360 2-hr gridpoint values, and a regional monthly average as the mean of 30 daily averages. The effect of the transient SST anomaly in the North Pacific Ocean on the computed eastern regional weather for the 3-mo winter season is indicated in table 1, in which are shown the regional average monthly and seasonal temperatures (°C) and total precipitation (cm) for the anomaly and control runs.

In view of the computational uncertainty noted earlier, no special significance should be attached to the numerical results in table 1. However, the magnitudes are interesting. Effects of the order of 1°–3°C in monthly and seasonal mean temperatures are indicated in the table by the differences, A−C. Over the eastern region of the United States in winter, the class limits used in monthly weather predictions by the National Weather Service (Namias 1953) [6] to separate the monthly mean temperature class "normal" from "above" and "below" normal span a range of only about 2°–3°F, or less than 2°C. The departure-from-normal class limits, which define the temperature prediction classes "much above" and "much below" normal, are approximately ±3°–6°F or only about ±2°–3°C. Thus, one effect of a transient SST anomaly in the North Pacific Ocean could possibly be to alter the monthly mean temperatures over the eastern United States by as much as two class intervals, if the model computations are credible.

For the purposes of monthly precipitation forecasting in winter in the eastern United States, the class limits used to separate "moderate" precipitation from "heavy" and "light", respectively, span a range of approximately 2 in. or less (i.e., no more than about 5 cm). As can be seen in table 1, effects of this magnitude can apparently be produced by a transient SST anomaly in the North Pacific Ocean, if the model computations are to be believed. Indeed, in the present experiment, the SST anomaly appears to have caused a consistent deficit of precipitation amounting to 12 cm (almost 5 in.) for the season over the eastern region. Thus, it appears that the influence of even a transient North Pacific SST anomaly on regional weather, over periods of at least months and seasons, may be significant in the sense that monthly (as well as seasonal) temperatures and precipitation can possibly be altered by as much as one or two class intervals. From the viewpoint of monthly and seasonal weather prediction, this is clearly a matter of some practical importance.

The version of the two-level Mintz-Arakawa model used for this experiment overpredicts global precipitation. This is primarily the result of an overprediction in the Tropics resulting from the parameterization of convection, which leads to an excess in the convective component of the precipitation. The global average precipitation for the 90-day period is 4.6 mm/day for the control run and 4.4 mm/day for the anomaly run, indicating an apparent reduction of less than 5 percent in the global precipitation due to the SST anomaly. The zonal average precipitation for the season in both runs shows a maximum at latitude 6°S, with 24.6 mm/day in the control run and 22.9 mm/day in the anomaly run, indicating a modest decrease (about 7 percent). At latitude 2°S, however, the anomaly run yields 9.2 mm/day compared with 19.0 mm/day for the control, a decline of about 50 percent. In view of the low level of credibility of the tropical precipitation values, no attempt has been made to trace the mechanism in the model that produced this startling remote effect of the North Pacific SST anomaly. Nevertheless, the computations again indicate the sensitivity of the model to relatively modest changes in sea-surface temperatures.

5. CONCLUSIONS

The experiments in seasonal weather computation with the global two-level Mintz-Arakawa model have shown that the model is sensitive both to the numerical differences associated with different computational algorithms and to the physical influence, as represented in the model, of the sea-surface temperatures. With a time step of 6 min, more than 2×10^4 steps are required to march out a 90-day forecast. The cumulative effect of the differences between alternative computational procedures over this many time steps results in a decorrelation of the alternative solutions, all other things being equal. Nor is the situation helped appreciably by time averaging. Monthly mean maps for the second and third months after the start of the computations are also decorrelated.

The sensitivity of the model to computational procedures raises serious questions regarding the credibility of the seasonal calculations. The SST anomaly experiments indicate that both persistent and transient sea-temperature variations of reasonable magnitude are capable of generating marked differences in surface and upper level pressure patterns, as well as significant long-term weather effects at remote places. There is, as yet, no reason to doubt that this behavior of the model may indeed reflect a similar sensitivity of the real atmosphere

[6] See also the *Average Monthly Weather Outlook* issued twice a month by the National Weather Service, Silver Spring, Md.

to the temperature of the sea surface. However, the computational sensitivity does suggest that the particular manner in which the model responds to an SST anomaly is probably not a credible reflection of nature. At this time, one can conclude only that the interaction between the atmosphere and the ocean introduces a significant element of indeterminacy in monthly and seasonal weather prediction.

ACKNOWLEDGMENTS

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PICTURE OF THE MONTH
Frontal Rope in the North Pacific

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A line of clouds or "frontal rope" is often, but not invariably, seen on high-resolution weather satellite data coincident with the leading edge of cold frontal systems traversing the central Pacific. Cloud tops along these lines, which are believed to be associated with convective rainshowers, have not been observed to exceed 12,000–

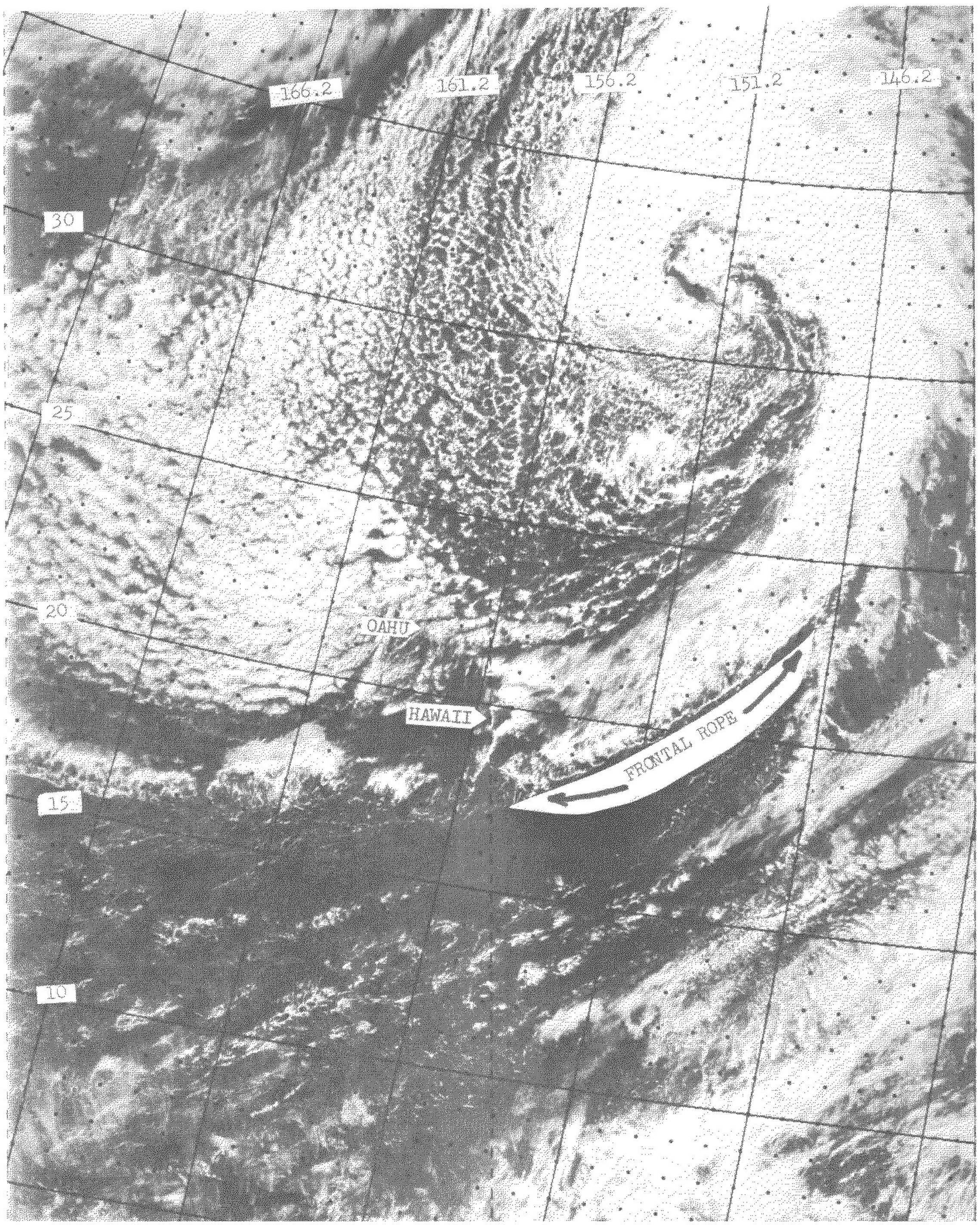

FIGURE 1.—Visual range DAPP data.

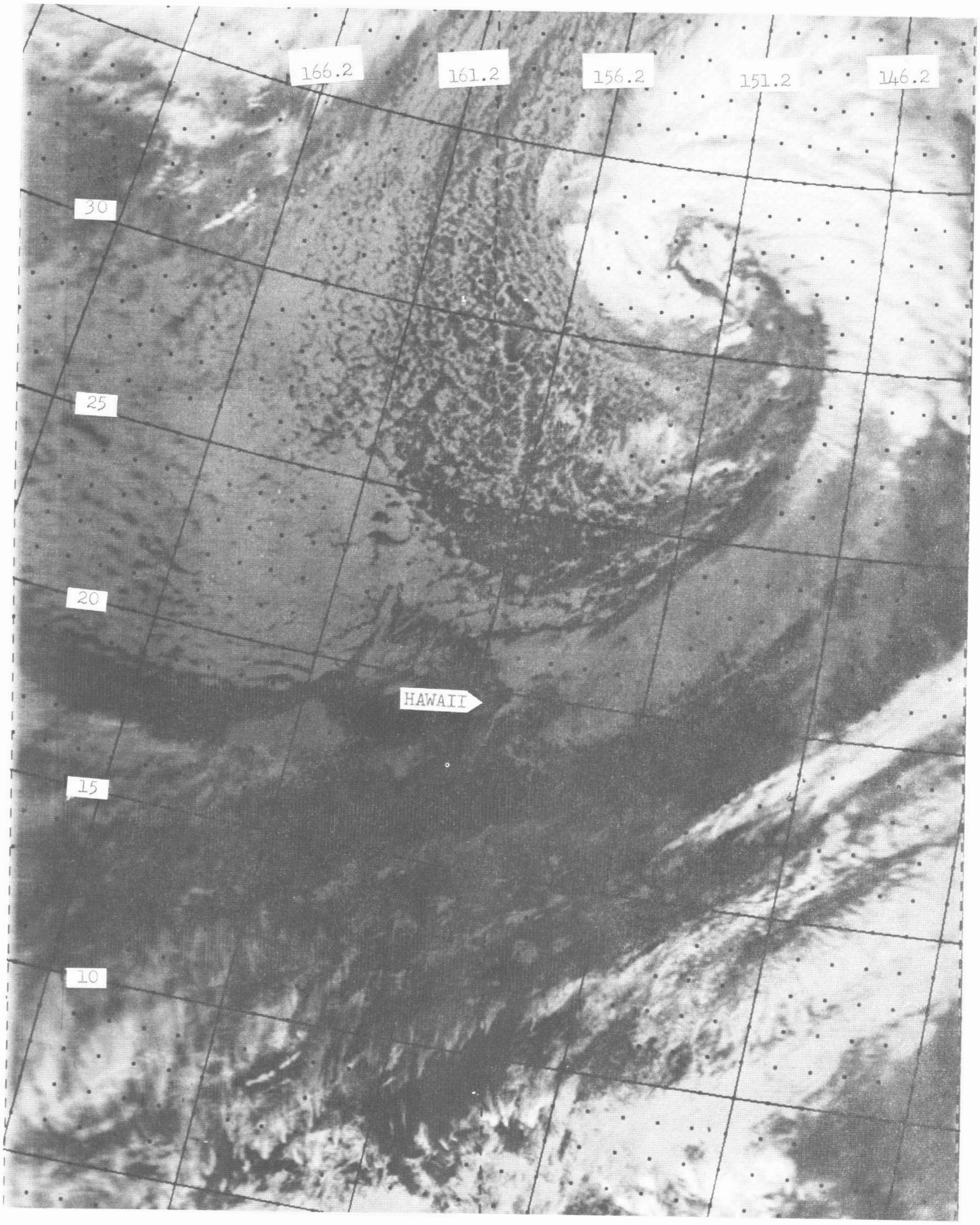

FIGURE 2.—Infrared range DAPP data.

15,000 ft during 2 yr of scrutiny. We are not aware of any cases of severe weather associated with these lines.

A late-season frontal system passed through the Hawaiian Islands on Apr. 4, 1973. The central Low in the system was centered at 32°N, 151°W, with the front extending from 35°N, 151°W, to just south of the island of Hawaii. The leading edge of this system, as shown by the visual range DAPP[1] data in figure 1, contains a frontal rope extending from 25°N, 145°W, to 18°N, 154°W. No severe weather or thunderstorms were observed in the islands as the front passed. Figure 2 is a corresponding presentation of infrared data in which cloud top temperatures are represented on a 16-shade gray scale, spread over a 100°C range. Lighter shades represent colder and, therefore, higher cloud tops. It is readily apparent that the frontal rope is totally within an area of relatively low clouds. Cloud tops along and in the vicinity of the frontal rope were estimated to have maximum heights of not more than 11,000 ft, with most tops below 9,000 ft. A detailed study revealed that the cloud tops were below the trade-wind inversion, at about

[1] DAPP is the Air Force's Data Acquisition and Processing Program, which provides simultaneous, high quality, real-time read out of visual and infrared scan-line data from meteorological sensors aboard a satellite at a nominal 450-n.mi. (satellite) orbiting altitude. Cloud elements of ½- and 2-n.mi. scales, respectively, may be resolved in the visual and infrared photographs presented. These data were acquired by the DAPP site located at Hickam Air Force Base, Hawaii, at approximately 2230 GMT on Apr. 4, 1973.

4,000 ft, along southern portions of the line.

The only significant weather thus far observed with a frontal rope has been moderate to heavy rain. Based on these observations, one is lead to conclude that cumulonimbus activity is rarely, if ever, associated with a frontal rope in the central Pacific. If convective clouds of the scale noted were associated with significant cumulonimbus activity, it is likely that a cirrus shield would completely obscure the line on the satellite data, thus precluding identification as a frontal rope.

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